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Carbon emissions from manufacturing energy use in 13 IEA countries: long-term trends through 1995

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Abstract

This paper analyses the evolution of carbon emissions from the manufacturing sectors of 13 IEA countries, based on national data at the 2 or 3 sector ISIC level of disaggregation. We carry out an Adaptive-Weighting-Divisia decomposition of changes into factors representing sub-sectoral branch energy intensities, output mix or structure, final fuel mix, and utility fuel mix. We also carry out a detailed comparison of emissions by country and sub-sector for 1994. We find that by the mid-1990s, emissions from manufacturing in most countries were close to their 1973 levels. The main reasons were lower branch energy intensities and in some countries changes in utility fuel mix. Changes in the mix of output had small downward effects in a few large countries (Japan and the United States), while these shifts increased emissions in others (Australia, Norway, Netherlands). Fuel mix changes lowered emissions slightly, principally through moves away from coal and oil towards gas. The comparison of countries shows that after overall output, energy intensities explain most of the differences in per capita emissions from manufacturing. Fuel mix and utility fuel mix play an important role for some countries with very CO_2 — free power sectors (Sweden, Norway, France) or CO_2 intensive power sectors (Australia). Some of the differences in energy intensities, however, arise because of hidden sub-sectoral mix effects that cannot be resolved at the 3-digit ISIC level of disaggregation. Emissions have been rising since 1990, largely because energy intensities are not falling as fast as they did before 1990. What this means for the Kyoto Accord and other concerns related to global carbon emissions remains to be seen.

Keywords: Industrial CO_2 emissions; Decomposition analysis; International comparisons

1. Introduction

This is the sixth paper in the series of studies of energy use and carbon emissions in manufacturing in IEA[3] countries. In the first three papers (Torvanger, 1991; Howarth *et al*., 1991; Schipper *et al*., 1993), we examined energy use and carbon emissions from manufacturing from 1971 to 1987 in nine IEA countries. This paper extends our recent analysis of energy use (Schipper *et al*., 1999, published in summary as Unander *et al*., 1999, hereafter referred to as Paper 1) to carbon emissions.[4] These papers expand the analysis of energy use and carbon emissions to 13 IEA countries — Australia, Canada, Denmark, France, Finland, West Germany,[5] Italy, Japan, Netherlands, Norway, Sweden, United Kingdom, United States[6] (which together we refer to as the IEA-13), and extend the period of observations to

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[3] IEA countries are Member countries of the International Energy Agency, part of the Organisation for Economic Co-operation and Development (OECD).

[4] Others papers in this series have examined the residential sector (Schipper *et al*., 1996), the travel sector (Scholl *et al*., 1996); the freight sector (Schipper *et al*., 1997a) and more recently the service sector (Krackeler *et al*., 1998).

[5] We use West Germany since our analysis mostly excludes the territory of the former East Germany in order to maintain comparable results after 1990. When our analysis includes manufacturing in unified Germany for the period 1990–1994 we refer to unified Germany as Germany.

[6] We use abbreviations for the United Kingdom — UK, and for the United States — US.

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Nomenclature

E_t	total sectoral energy consumption in year t
E_{it}	energy consumption in end use i in year t
E_{ijt}	energy consumption of fuel j in end use i in year t
e_{jt}	share of energy consumption of fuel j in end use i in year t, given by, E_{ijt}/E_{it}
Y_t	total activity in year t
Y_{it}	activity in end use i in year t
y_{it}	share of total activity in end use i in year t, given by, Y_{it}/Y_t
I_t	total sectoral energy intensity in year t given by E_t/Y_t
I_{it}	energy intensity of end use i in year t given by E_{it}/Y_{it}
C_t	total sectoral carbon emissions in year t
C_{it}	carbon emissions from end use i in year t
C_{ijt}	carbon emissions from fuel j in end use i in year t
c_{it}	share of carbon emissions from end use i in year t, given by, C_{it}/C_t
c_{ijt}	share of carbon emissions from fuel j in end use i in year t, given by, C_{ijt}/C_t
R_{ijt}	carbon emissions per unit of fuel j in end use i in year t, given by, C_{ijt}/E_{ijt} (The term R_{ijt} essentially measures changes in the carbon intensity of electricity, since the primary fuel mix used to generate electricity changes over time whereas the carbon intensity of other final fuel types (e.g., oil and natural gas) are assumed to stay constant over time.)
$(1 + \%\Delta C_{\mathrm{tot}})_{0t}$	index of actual change in carbon emissions between year 0 and t, where 0 is the first year of a period. Defined as the product of $(1 + \%\Delta C_{\mathrm{emissions}})_{0t}$, $(1 + \%\Delta C_{\mathrm{fuelmix}})_{0t}$, $(1 + \%\Delta C_{\mathrm{intensity}})_{0t}$, $(1 + \%\Delta C_{\mathrm{structure}})_{0t}$, and $(1 + D)_{0t}$ for a four-term index decomposition
$(1 + \%\Delta C_{\mathrm{emissions}})_{0t}$	index component estimating the change in carbon emissions due to changes the carbon intensity of fuels between year 0 and t
$(1 + \%\Delta C_{\mathrm{fuelmix}})_{0t}$	index component estimating the change in carbon emissions due to changes in the final fuel mix between year 0 and t
$(1 + \%\Delta C_{\mathrm{intensity}})_{0t}$	index component estimating the change in carbon emissions due to changes in final energy intensities between year 0 and t
$(1 + \%\Delta C_{\mathrm{structure}})_{0t}$	index component estimating the change in carbon emissions due to changes in the activity mix between year 0 and t
D_{0t}	quotient of actual carbon emissions to estimated carbon emissions (residual of estimation)

1994 or 1995. This allows us to assess emissions trends since 1990, the base year for climate negotiations. Subsequently, we apply a more advanced method of index decomposition to energy use and carbon emissions (Greening *et al*., 1996, 1997; see also Schipper *et al*., 1997b).

The objectives of this paper are fourfold. First, we quantify emissions from manufacturing in six subsectors and remaining manufacturing, decompose these emissions over the past 25 years into five factors that affected changes in the aggregate volume of carbon emissions, and compare the results across countries. Second, we examine the role of refining and the "other industries" — agriculture, construction, and mining — as sources of carbon emissions from industry. Third, we briefly discuss causes underlying the carbon emission trends. Fourth, we contrast emissions trends from 1990 to 1995 with previous years in order to draw conclusions about prospects for future restraint of carbon emissions.

2. Aggregate trends in carbon emissions and energy use

Fig. 1 shows the evolution of emissions by sector for the 13 countries studied. We give emissions per unit of countries' total GDP[7] for 1973 and 1994 for most countries (1984 and 1994 for Australia, Canada, and Netherlands due to missing data for some sectors). Immediately clear from the figure is the declining importance of manufacturing carbon emissions per GDP in all the countries. The manufacturing share of total emissions

[7] All monetary units in this study are constant 1990 US dollars adjusted for purchasing power parity.

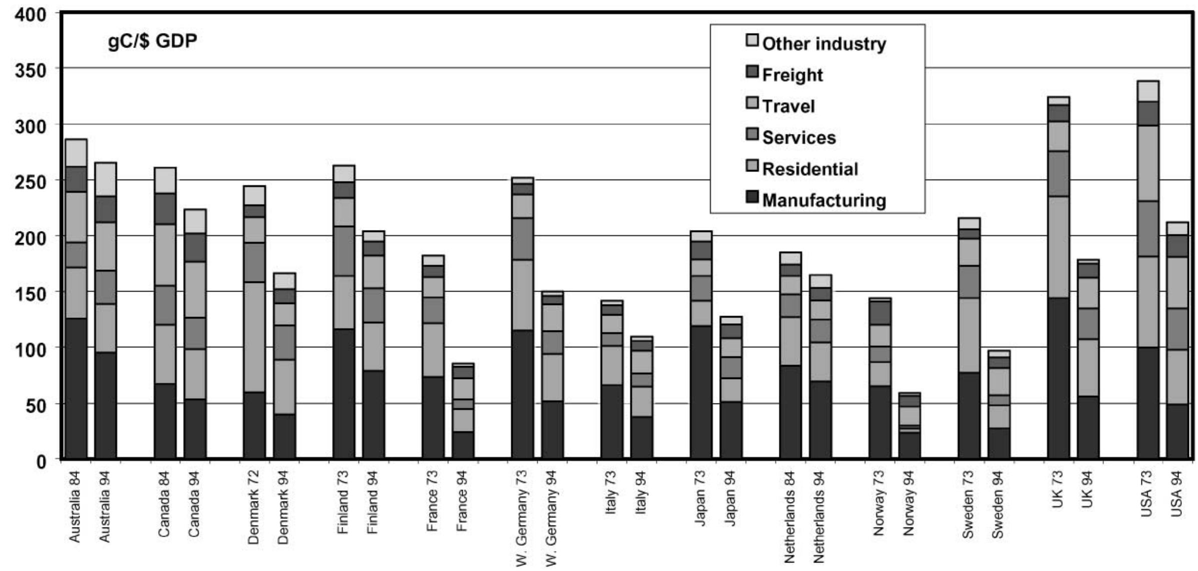


Fig. 1. Carbon emissions per GDP by sector.

also fell in every country but Finland. To understand these trends, we have to explore each of the components of changing emissions.

Trends in output, energy use, and fuel mix were examined in detail in Paper 1. Manufacturing value added increased 130% between 1970 and 1995 in the IEA-13, growing from $1279 billion to $2947 billion in 1995, an average of 3.3% per year. The fastest growth over the period was achieved by Japan, Italy, Finland, and the US, while the slowest growth occurred in the UK, Norway, Canada, and West Germany. Recessions marked three periods, 1974/1975, 1980–1982/1983, and 1990/1992. The largest decline of 6% in manufacturing output happened after the first oil price shock in 1973.

Growth was not uniform across all sectors. Heavy industry[8] in Canada, Japan, and the US lost some share of total output, enough to reduce manufacturing energy use between 9 and 14%. By contrast, the same sectors picked up some share of total output in Norway, Netherlands and Australia, which slightly boosted energy use. Nevertheless, by 1995, total output in the energy-intensive industries was 43% higher than in 1973. Thus, heavy industry was not "exported" from this group of countries on the whole, and neither were emissions of carbon. Including refining has little impact on this important conclusion.

Declining fuel intensity and fuel demand steadily reduced delivered energy[9] consumption in manufacturing in the majority of the IEA-13 countries, during the period from 1970 to 1994. Despite some policies favoring the use of coal in place of oil or gas, the fuel mix continued its evolution away from coal. The extent to which increases in natural gas or oil consumption replaced coal varied from country to country. At the same time electricity demand grew strongly in all countries. Electricity picked up market share predominantly due to the direct substitution of fuels for steam or heat, or due to the greater prevalence of certain electro-technologies that indirectly substitute for fuel use, such as thermomechanical pulping or electric arc steel. In Norway and Australia electricity gained market share because the output of key electricity-intensive industries, especially primary aluminum production, increased more rapidly than for industry as a whole. These changes in fuel mix are important since purchased electricity and heat generally emit more carbon per unit of delivered energy.

Carbon emissions from manufacturing, including refining, normalized to manufacturing GDP are presented in Fig. 2 for 1973[10] and 1994. We disaggregate these by major branch, counting all emissions from the non-energy-intensive branches in a residual "other manufacturing". Additionally, a marker on each bar shows the proportional contribution of emissions embodied in purchased electricity and heat. Through decomposition of carbon emissions we examine the factors that led to the decline in carbon emissions in manufacturing.

3. Methodology and data

To account for changes in carbon emissions due to fuel switching, we expand our factorial three-term index decomposition specification described in Paper 1 (which decomposes changes in output, energy intensity, and

[8] Heavy industry includes paper & pulp, chemicals, non-metallic minerals, ferrous metals, and non-ferrous metals manufacturing.

[9] Delivered energy here means the same as final energy, or site energy.

[10] 1979 for Canada and 1980 for Netherlands, due to lack of reliable data.

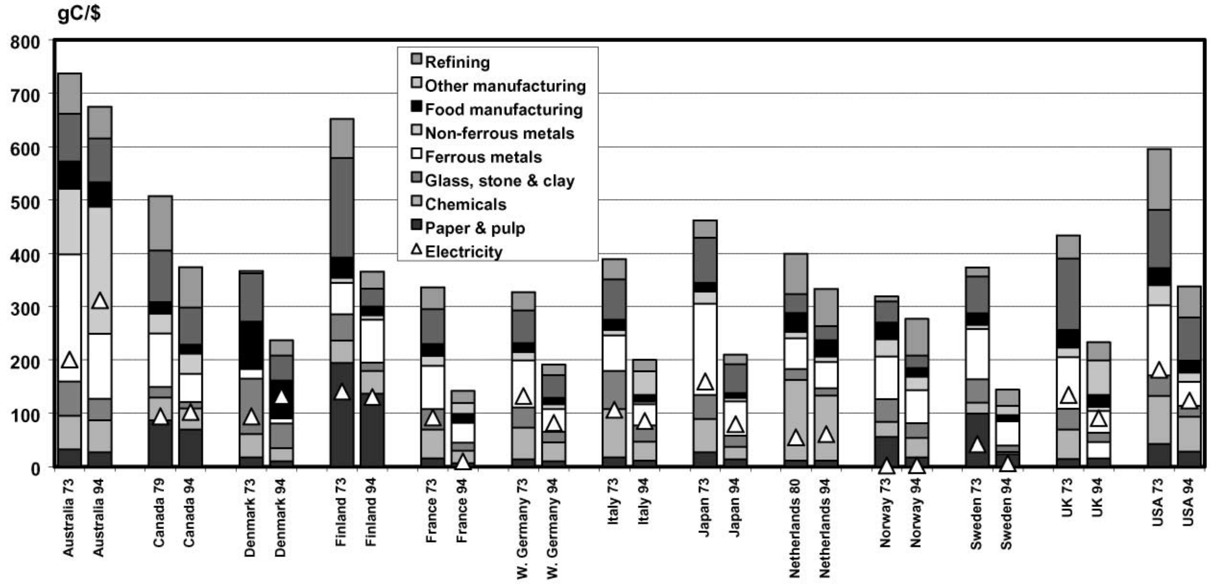


Fig. 2. Manufacturing carbon emissions per value added by subsector, including refining.

economic structure) to add additional terms for fuel mix. This includes not only the consumption of delivered energy, but also fuels used in the generation of electricity and district heat. Using a rolling Adaptive Weighting Divisia (AWD) index decomposition (based on work presented in Liu *et al*., 1992), we measure the impacts of changes in output, subsectoral energy intensity, fuel mix, power generation (utility) mix, and the structure of output on total carbon emissions (see Appendix A). We evaluate changes in each country's manufacturing carbon emissions and compare changes over time by country (Greening *et al*., 1996).

In this paper we have revised data from most countries studied in Greening *et al*. (1996) (particularly Denmark, US, Japan) as new official data were made available that included revisions from the late 1980s or early 1990s. The reader should note that the data sources are official national sources, mostly industry statistics, which have more detail at the 2- or 3-digit International Standard Industrial Classification (ISIC) level than most national energy balances. We measure delivered energy for each fuel, including purchased district heat and electricity as well as non-commercial fuels such as wood or paper residues, and present the energy content of fuels in net calorific values.[11]

As described in Paper 1, output is measured as value added components of GDP originating in each subsector of manufacturing. Value added comes from the OECD's STAN database, which is the most thorough reconciliation of national value-added data, except for Sweden and Australia, where the OECD advised us to use the national data made available to us by national authorities. For Italy data permitting separation of ferrous from non-ferrous metals and pulp/paper from printing are not available, while for the UK our separations are estimated from various years where such disaggregations are available.

Carbon emissions from fuels consumed are calculated using the simplified carbon factors for main fuels according to the IPCC methodology[12] (IPCC, 1996). Carbon factors for electricity or heat generation are equal to the amount of emissions generated from fuel inputs per unit of delivered electricity or heat. Data on electricity generated by thermal power plants, autoproducers of electricity,[13] public and autoproducer combined heat and power plants (CHP and ACHP),[14] and heat generated by public heat plants[15] and autoproducer[16] heat plants are taken

[11] The energy content of fuel can be measured as heat of fuel before vaporization (gross calorific value), or after vaporization (net calorific value). The energy released during vaporization mostly cannot be captured and used for energy purposes, therefore, we present fuels in net calorific values. For Australia, Canada, Japan, UK and US the energy data have been converted from gross calorific values to net calorific values, using approximate values for main fuel categories. Energy balances of the remaining IEA-13 present fuels in net calorific values. In our previous work we did not convert energy consumption data to net calorific values.

[12] The simplified carbon factor for oil and oil products is 21.1 ktC/PJ, 15.3 ktC/PJ for natural gas, and 25.8 ktC/PJ for coal.

[13] Autoproducer undertakings are industrial power generation facilities that produce electricity wholly or partly for their own use. Electricity production reported for Autoproducer Electricity or Autoproducer CHP is the total quantity of electricity generated (IEA, 1998).

[14] Autoproducer CHP plants are industrial combined heat and power plants. Autoproducer undertakings generate electricity and heat, wholly or partly for their own use as an activity that supports their primary activity. They may be privately or publicly owned.

[15] Including heat pumps and electric boilers.

[16] Autoproducer heat plants are industrial heat plants that produce heat wholly or partly for their own use. Heat production reported for autoproducer CHP and autoproducer heat plants should comprise only the heat sold to third parties. Heat consumed by autoproducers is included in the final consumption numbers of the respective end-use sector.

Table 1
1973–1994 average annual rates of change in actual energy consumption in IEA-13, from activity, structure and intensity effects

Country	Actual			Activity			Structure			Intensity		
	Electricity (%)	Final (%)	Primary (%)	Electricity (%)	Final (%)	Primary (%)	Electricity (%)	Final (%)	Primary (%)	Electricity (%)	Final (%)	Primary (%)
Australia	4.9	0.9	1.5	2.4	2.4	2.4	0.1	0.1	0.1	2.4	−1.1	−1.0
Canada[a]	2.6	0.4	1.0	1.5	1.5	1.5	0.4	−0.2	−0.1	0.7	−0.8	−0.3
Denmark	3.4	−2.3	−1.4	1.3	1.3	1.3	0.2	−0.3	−0.2	1.9	−3.3	−2.5
Finland	4.0	1.5	2.7	2.7	2.7	2.7	0.2	0.3	0.3	1.1	−1.6	−0.3
France	1.2	−1.0	−0.1	1.3	1.3	1.3	0.3	−0.1	0.0	−0.4	−2.2	−1.4
W. Germany	1.2	−1.1	−0.7	0.9	0.9	0.9	0.2	−0.1	0.0	0.0	−1.9	−1.6
Italy	1.9	−0.5	−0.1	2.9	2.9	2.9	0.3	0.1	0.2	−1.3	−3.6	−3.2
Japan	1.7	−0.5	0.3	3.1	3.1	3.1	−0.8	−1.2	−1.1	−0.5	−2.3	−1.7
Netherlands[a]	1.5	0.2	0.8	1.8	1.8	1.8	0.2	0.8	0.7	−0.6	−2.4	−1.8
Norway	1.1	0.1	0.2	0.4	0.4	0.4	1.2	0.9	1.0	−0.5	−1.3	−1.3
Sweden	1.5	−0.9	0.7	1.3	1.3	1.3	0.4	0.3	0.3	−0.2	−2.5	−0.9
UK	0.7	−2.7	−2.0	0.3	0.3	0.3	−0.1	−0.4	−0.3	0.6	−2.6	−2.0
US	1.4	0.0	0.6	2.1	2.1	2.1	−0.4	−0.8	−0.7	−0.3	−1.4	−0.9

[a] Average annual rates of change for Canada are for 1979–1994 and for Netherlands are 1980–1994.

from International Energy Agency (IEA) Extended Energy Balances (IEA, 1998). In order to separate electricity inputs from heat inputs into CHP and AHP generation, we assume that those inputs are proportional to the heat and electricity outputs from CHP and AHP generation.[17] We calculate carbon factors for electricity generation by the central power system by multiplying each fuel[18] input into electricity generation by its respective carbon factor, according to the IPCC methodology. Using the same methodology we calculate the carbon factor for heat production by central power systems.

4. Results

4.1. Energy consumption

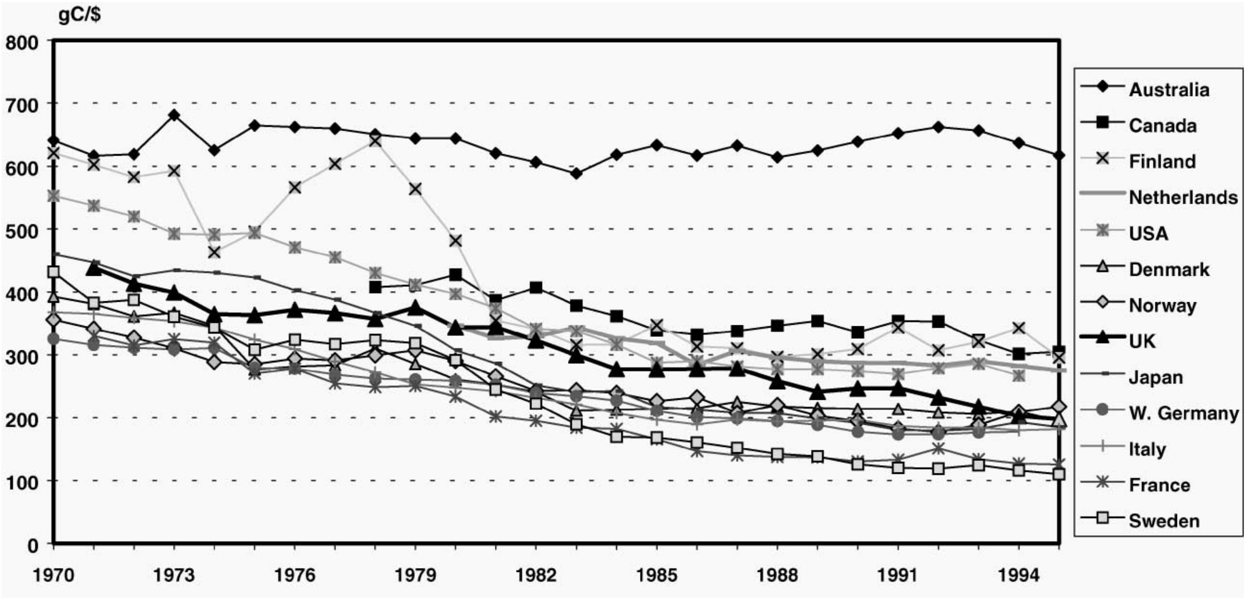
Delivered manufacturing[19] energy consumption declined in eight of the IEA-13 countries (see Table 1). Primary energy consumption declined in six countries, while electricity consumption increased in all countries. Output had a positive effect on electricity, delivered, and primary energy consumption in each of the IEA-13 countries. In contrast, reductions in energy intensity led to a decline in delivered and primary energy use in all countries. However, electricity intensity increased in five countries — Australia, Canada, Denmark, Finland, and the UK. The increase in aggregate electricity intensity in Australia and Canada was caused by the growth in primary aluminum production, an extremely electricity-intensive industry. Such structural shifts were not sufficient to account for the increased aggregate electricity intensity in Denmark and Finland. Rather, some branches became more electricity-intensive, which for Finland could also have been caused by less self-generation of electricity and more purchases of electricity. Overall, however, changes in the structure of manufacturing had less of an overall effect on energy consumption than changes in output and energy intensity. But the structure of manufacturing output became less energy-intensive in seven of the IEA-13 countries.

Fig. 3 shows aggregate emissions per unit of GDP in manufacturing for each country from 1970 through 1994/1995. The decline is evident, as is the large spread in values among countries. Australia's carbon intensity was almost 3 times the average carbon intensity of the other countries in 1994. The other countries can be divided into two groups based on manufacturing carbon intensity: the medium-carbon intensity countries (Canada, Finland,

[17] Thus, electricity inputs will contain all fuel inputs into electricity plants and electricity inputs into CHP, while heat inputs will contain all fuel inputs into heat plants, heat pumps, electric boilers, and heat inputs into CHP.

[18] We assign zero emissions from the use of biomass fuels.

[19] Excluding refining.



Note: Countries are presented in descending order according to their 1995 values.

Fig. 3. Aggregate carbon intensity: emissions per unit of manufacturing value added.

Netherlands, the US and Denmark), and the low-carbon intensity countries (all remaining countries). In those countries where the share of manufacturing in GDP declined significantly (Norway, the UK and Australia), the drop in the emissions/total GDP ratio is even larger, as may be evident from Fig. 1. Indeed, differences in output per capita help explain much of the differences in overall manufacturing emissions per capita among countries.

Aggregate carbon intensities lie within a range of 56% around an average for all 13 countries, except for Australia, whose intensity is greater than 2 times the mean. What accounts for the great differences in emissions per unit of aggregate output between the countries? Three factors come to mind immediately: differences in energy use per unit of output at the level of individual branches of industry, differences in the composition of output, as measured by the share of each branch in manufacturing output, and finally differences in the ratio of carbon to delivered energy consumed by industry. As stated above, the carbon content per unit of energy may vary either due to differences in final fuel mix or differences in the fuel mix used by utilities. Since the latter effect is beyond the control of the end-users, we treat it separately from the final fuel mix effect.

Decomposition of changes in carbon emissions can be summarized by the relation that has come to be known by "ASIF". Put simply, we relate emissions **G** to four multiplicative terms:

$$\mathbf{G} = \mathbf{A} \sum_{i=1}^{n} \sum_{j=1}^{n} [\mathbf{S}_i \mathbf{I}_i \mathbf{F}_{ij}].$$

In this decomposition, **A** represents overall sectoral activity (say GDP in manufacturing), **S** represents sectoral structure (shares of output by 2- or 3-digit ISIC branch). **I** represents the energy intensity of each branch i shown in **S** (in energy use/real money output). **F** is the carbon content of each fuel j used in branch i. The j index captures the effects of changes in fuel mix at both the end-user and utility levels as well as variations in the efficiency of generating and distributing electricity and district heat. The three right-hand terms sum to what we refer to as the aggregate carbon intensity. In the remainder of this section we use the above equation to estimate the relative weight of each term in determining the differences in actual carbon emissions. We then discuss the results of our AWD decomposition, which isolates the contribution that each of the terms has made to the evolution of each country's emissions.

4.2. Static comparisons of carbon emissions

To see how important different components of manufacturing carbon emissions are, we use a novel decomposition method we have called "Mine/Yours" (Schipper *et al*., 1999). Fig. 4 depicts a simplified two-term decomposition. The first bar shows the actual per capita carbon emissions from manufacturing for each country, which demonstrates wide variation. The second bar shows what those emissions would be with actual carbon intensity but the IEA-13 average manufacturing output/capita. The third bar portrays the calculation with the actual output/capita but the average carbon intensity. Variations in output per capita are a significant

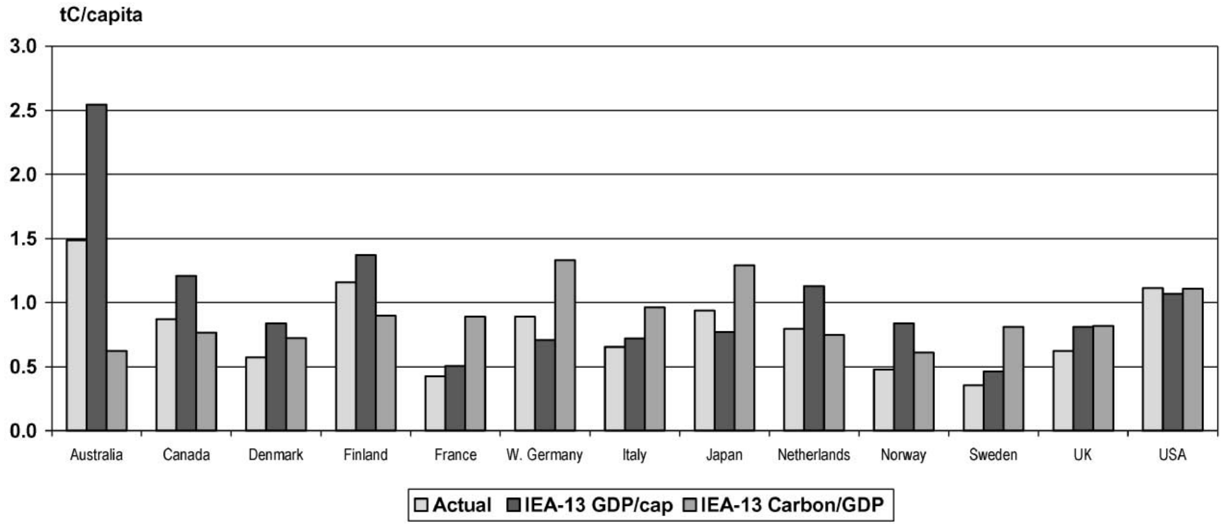


Fig. 4. Emissions per capita, 1994 actual and at average output and carbon intensity.

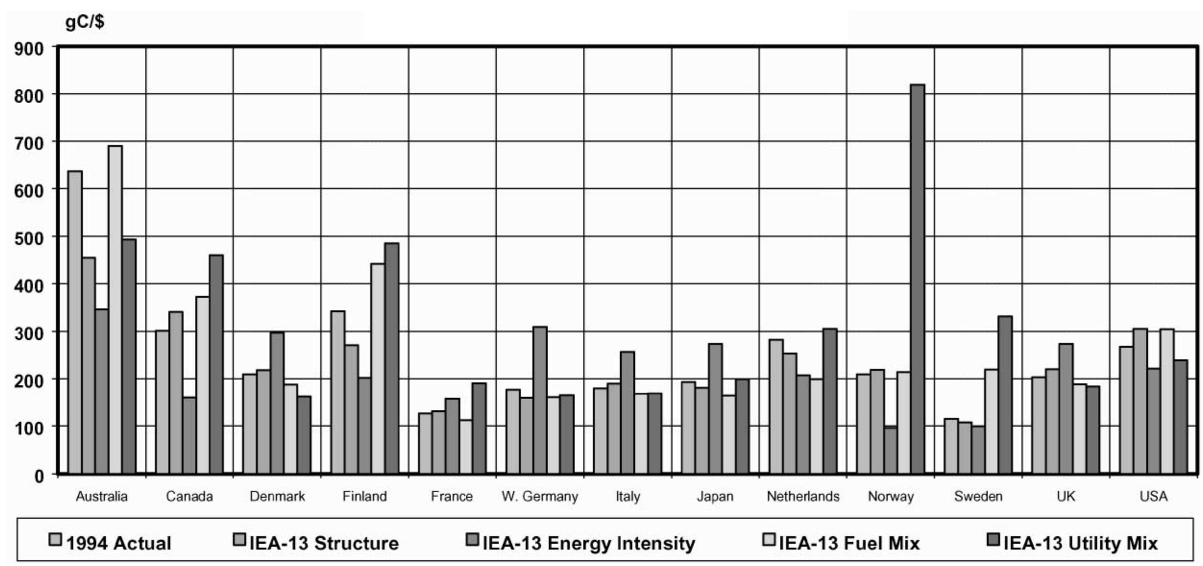


Fig. 5. Carbon intensity: 1994 actual and at IEA-13 structure, intensity, fuel mix and utility mix.

determinant of the differences in per capita emissions, but aggregate carbon intensity has an even greater impact. Variance in the percentage changes from substituting IEA-13 output/capita is only 9%, compared to 26% when we substitute IEA-13 carbon intensity. Since output per capita is not a factor policies are likely to suppress, action to restrain emissions will have to focus on the components of carbon intensity.

Fig. 5 carries the Mine/Yours analysis further to examine the components that affect aggregate carbon intensity. We calculate the 1994 weighted IEA-13 average for each of the AWD decomposition factors and call them normalized factors. Then by substituting each normalized factor value for each country while holding other factors constant we calculate a new hypothetical carbon intensity. For example, we calculate the importance of average output structure to aggregate carbon intensity in each country by multiplying each country's subsectoral carbon intensities by the respective shares of the subsectoral output that make up the average for IEA-13 countries. By comparing actual aggregate carbon intensity with what we obtain from the Mine/Yours substitution, we see how much the country's actual structure causes its emissions to deviate from the "average" we have constructed. We estimate the importance of energy intensity by multiplying each country's subsectoral output by the IEA-13 average subsectoral energy intensity, at the country's actual ratio of carbon emitted per unit of delivered energy use. Measuring the impact of final fuel mix, we multiply each country's energy intensity by the carbon content of the average final fuel mix of all countries (using each country's own utility carbon emissions coefficient). Finally, we measure the importance of the utility fuel mix by multiplying each country's electricity and district heat contribution to carbon emissions by the respective IEA-13 average carbon factors for electricity and heat. If the carbon intensity shown falls when a Mine/Yours average is substituted for a given country, then that country was more carbon-intensive in that respect than the average for the IEA-13, and vice versa. Further, we compare the importance of each individual factor by noting how much the hypothetical carbon intensity changes from the actual intensity when that factor is substituted.

Differences in the structure of manufacturing output, followed by the differences in final fuel mix, had the least effect among other factors on the spread in aggregate carbon intensity among the IEA-13.[20] The variance around the average is only 2 and 9% for these two components, respectively. Substitution of this factor had the largest impact only in Netherlands. Substitution for energy intensity was the predominant factor in seven countries. If all countries had the average IEA-13 energy intensity, the aggregate carbon intensity would have increased by 74% in Germany, 42% in Italy and Japan, and 35% in the UK. However, in Netherlands the IEA-13 average energy intensity would have reduced aggregate carbon intensity by 27%. Substitution for the utility fuel mix had the largest effect in Canada, Finland, France, Norway, and Sweden. The results of the utility mix substitution are particularly striking for Sweden and Norway, where carbon emissions would, respectively, nearly triple and quadruple. These huge gaps reflect the low-carbon intensity of the power generation sector in those countries resulting from the high share of hydro- and nuclear power sources. The magnitude of the effect also depends on the share of electricity and district heat in the final fuel mix, which in Norway is much higher than the other IEA-13 countries.

Table 2 shows in more detail how differences in subsectoral output shares and carbon intensities affect aggregate carbon intensity. It summarizes the individual branch carbon intensities for each country in 1994, as well as each branch's respective share in output. The aggregate carbon intensity equals the sum of the branch intensities weighted by their output shares. Table 2 shows that manufacturing structure is relatively homogenous within the IEA-13. The combined share of food processing and other manufacturing, which are on average much less

[20] It is important to keep in mind the influence of the US on the results. In 1994, the US accounted for 38% of IEA-13 manufacturing value added and 45% of emissions. The result of the US subsectoral energy intensity substitution falls another 17% to 184 gC/$ when the average energy intensities of the other 12 countries is used.

Table 2
Subsectoral carbon intensities of IEA-13, and the respective shares of each branch in total manufacturing output in 1994[a]

Country	Carbon intensity (gC/90 USD)								Share of output in manufacturing GDP[a]						
	Total	Paper & pulp	Chemicals	Glass, stone & clay	Ferrous metals	Non-ferrous metals	Food Processing	Other	Paper & pulp (%)	Chemicals (%)	Glass, stone & clay (%)	Ferrous metals (%)	Non-ferrous metals (%)	Food Processing (%)	Other (%)
Australia	637	1053	826	773	2813	3426	253	157	3	7	5	4	7	19	54
Canada	301	838	1150	582	1653	1082	110	109	8	3	2	3	4	15	64
Denmark	210	429	244	1127	1057	483	325	77	3	10	4	1	0	21	61
Finland	342	999	622	462	2164	634	148	59	14	7	3	4	1	12	59
France	127	273	227	382	1184	192	97	35	3	11	4	3	2	15	62
W. Germany	178	361	319	458	782	392	112	71	3	12	4	6	2	11	62
Italy	180	427	472	459	1068	539	114	66	3	8	7	4	1	11	67
Japan	193	563	259	573	1081	446	83	81	2	9	4	6	2	10	67
Netherlands	282	338	787	400	1867	887	181	52	4	17	4	3	1	18	54
Norway	209	283	440	910	2151	429	78	44	6	8	3	3	6	20	53
Sweden	116	226	54	565	1085	203	84	29	10	9	2	4	2	10	62
UK	203	459	236	484	1470	889	162	106	3	13	4	3	1	14	62
US	267	622	575	876	1688	1094	225	123	5	12	2	3	2	10	67

[a] Note: the total may not equal to 100 due to independent rounding.

carbon-intensive than the raw materials industries, ranges only from 71% in Finland to 82% in Denmark. What is by far more important in determining aggregate carbon intensity is the tremendous variation in branch carbon intensities. For example, Australian aggregate carbon intensity would be about 30% lower if the carbon intensity of its non-ferrous industry were the same as the IEA-13 average carbon intensity. The difference of subsectoral carbon emissions per unit of output in large part reflects variation in subsectoral energy intensities caused by the differences in energy-using technologies in manufacturing industries in these countries (Paper 1). In some cases, particularly for non-ferrous metals, chemicals, or paper and pulp, structural differences account for much of the variation in intensities within the same branch (e.g., primary vs. secondary aluminum, pulp vs. paper, etc.). As an example, Australia produces a large amount of primary aluminum, while Japan and Italy now produce almost entirely secondary (recycled) aluminum.

Other factors besides energy efficiency also play an important role in determining subsectoral carbon intensity. Countries with low-cost hydro- or nuclear electricity often have heavy concentrations of electricity-intensive industries, but Australia is a notable exception. With low-cost coal-fired electricity, Australia has a relatively electricity-intensive structure due to its large non-ferrous metals industry. For countries relying mostly on hydro- or nuclear power low-carbon electricity offsets the energy-intensive structure of manufacturing in limiting carbon emissions. In Netherlands, which has a huge chemicals sector, the energy-intensive structure combined with carbon-based power sources results in a relatively high carbon intensity in manufacturing even though their industries are relatively energy efficient. These examples illustrate why the carbon intensities in Table 2 must be treated with care; such comparisons cannot be readily used to estimate the potential for energy- or carbon-saving technologies.

4.3. Changes in carbon emissions over time

Past changes in carbon emissions and intensity give clues to future trends. As with our Mine/Yours comparisons, we begin with changes in total output and changes in aggregate intensity. Fig. 6 shows how these two components affected total output between the earliest year for which data were available and 1994/1995. Without further decomposition we can say that both components varied by significant amounts. It can be observed that if total sectoral output changed while other components stayed constant at their 1973 levels, carbon emissions would have increased from 6% in the UK to 91% in Japan from 1973 to 1994. Among all of the emissions decomposition terms the activity effect was the largest determinant of emissions trends in Australia, Finland, Italy, Japan, and the US. Note that in Australia and Finland overall emissions rose, while in the other three countries emissions still fell because changes in the components of aggregate carbon intensity outweighed output growth. If carbon intensity changed while other components remained constant, aggregate carbon emissions would have declined from just 6% in Australia to 68% in Sweden. As noted previously, no country counts on restraining output as part of a carbon restraint strategy. Hence, it is the components of carbon intensity that must fall.

Changes over time in aggregate carbon intensity can be factored into four components: changes in the structure of output, changes in subsectoral energy intensity, changes in subsectoral final fuel mix used, and changes in utility fuel mix. Using the AWD index (see Appendix A), we calculate the cumulative indices of change in aggreg-

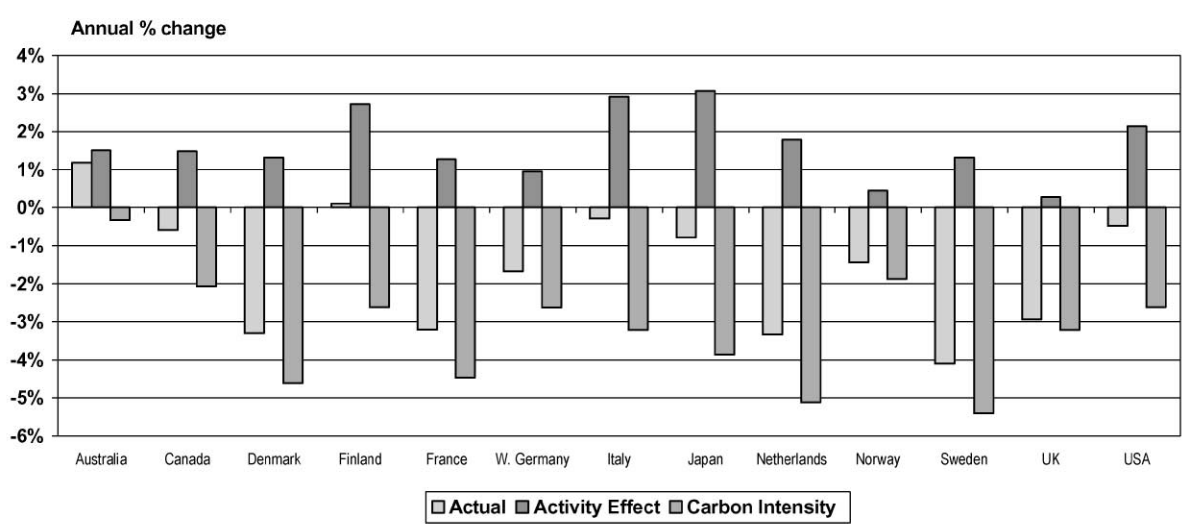


Fig. 6. Changes in actual emissions, activity, and carbon intensity, 1973–1994.

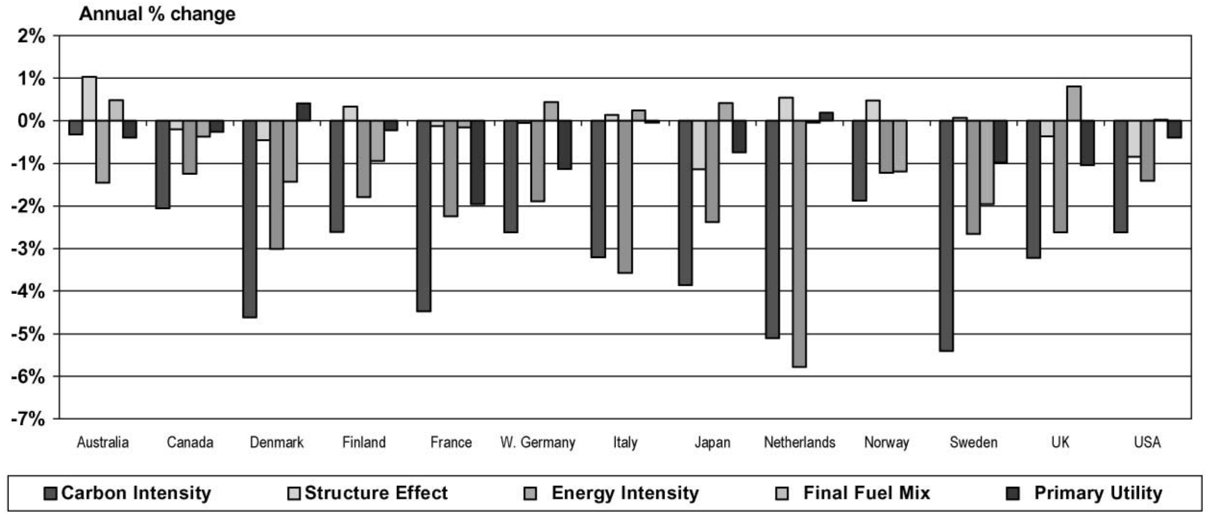


Fig. 7. Decomposition of changes in aggregate carbon intensity, 1973–1994.

Table 3
Contribution of each effect to the total avg. ann. rate of change in emissions intensity, 1973–1994

Country	Actual (%)	Activity effect (%)	Carbon intensity (%)	Structure effect (%)	Energy intensity (%)	Final fuel mix (%)	Primary utility (%)
Australia	1.2	2.4	− 1.2	0.1	− 1.4	0.5	− 0.4
Canada	− 0.6	1.5	− 2.1	− 0.2	− 1.2	− 0.4	− 0.3
Denmark	− 3.3	1.3	− 4.6	− 0.5	− 3.0	− 1.4	0.4
Finland	0.1	2.7	− 2.6	0.3	− 1.8	− 0.9	− 0.2
France	− 3.2	1.3	− 4.5	− 0.1	− 2.2	− 0.2	− 2.0
W. Germany	− 1.7	0.9	− 2.6	0.0	− 1.9	0.4	− 1.1
Italy	− 0.3	2.9	− 3.2	0.1	− 3.6	0.2	0.0
Japan	− 0.8	3.1	− 3.9	− 1.1	− 2.4	0.4	− 0.7
Netherlands	− 3.3	1.8	− 5.1	0.5	− 5.8	0.0	0.2
Norway	− 1.4	0.4	− 1.9	0.5	− 1.2	− 1.2	0.0
Sweden	− 4.1	1.3	− 5.4	0.1	− 2.7	− 2.0	− 1.0
UK	− 2.9	0.3	− 3.2	− 0.4	− 2.6	0.8	− 1.0
US	− 0.5	2.1	− 2.6	− 0.8	− 1.4	0.0	− 0.4
IEA-13 average	− 1.6	1.7	− 3.3	− 0.1	− 2.4	− 0.3	− 0.5

ate carbon intensity for each component. Fig. 7 illustrates how each decomposition factor affected the evolution of aggregate carbon intensity.

Changes in the structure of output have a mixed effect on aggregate carbon emissions. This caused carbon emissions to decline in four countries, from 3% in Canada to 21% in Japan from 1973 to 1994. The same effect caused carbon emissions to increase in Australia, Finland, Norway, and Netherlands, leaving emissions little changed in the other countries. In most countries the effect of structural change on aggregate emissions was closely related to the change in share of energy-intensive manufacturing in total manufacturing GDP. In Norway and Australia increases in the share of energy-intensive manufacturing outpaced the structural effect, while in France and the UK the decline in share of energy-intensive manufacturing was slower than the structural effect. These trends can be explained by structural changes at a subsectoral level, e.g., a switch to higher value added and lower carbon intensity manufacturing (e.g., higher value added chemicals, paper, steel alloys, etc.).

Changes in energy intensity would have reduced aggregate carbon intensity in all the countries with the largest reductions in Italy, Sweden, and the UK. The chemicals industry showed the largest reductions with energy intensity falling by almost half. Ferrous metals, non-metallic minerals, and other manufacturing industries also experienced marked reductions in energy intensity. It was the predominant term in every IEA-13 country. Similarly, changes in the fuel mix of power and heat generation and improvements in the efficiency of fuel conversion in utilities would have reduced aggregate carbon intensity in all the countries, except Norway, where the share of hydro (99%) in total power production remained unchanged. This effect had the largest impact in France where nuclear power in the electricity generation mix increased from 11 to 83%. Changes in fuel mix have a mixed effect on aggregate carbon intensities. If all other components remained at their 1990 level, changes in fuel mix would have reduced carbon intensity in six countries. Norway, Sweden, and Denmark experienced the largest reductions due to this effect. Declining oil use in all of these countries accounted for some decreasing carbon intensity due to this effect. In Denmark natural gas use increased from virtually zero consumption to about one-fourth of delivered energy use. In Norway and Sweden increasing shares of electricity and wood helped reduce emissions. Overall, the energy intensity effect contributed most to the declining carbon intensity in the IEA-13, restraining emissions in every country (see Table 3).

That so many factors may lead to reduced emissions is encouraging for the future. Unfortunately, since 1990, the base year for Kyoto negotiations, the various components restraining emissions have been much weaker than previously.[21] Thus, optimism about what these 20-year trends portend for the future had best be guarded.

5. Emissions from refining and other non-manufacturing industries

5.1. Impact on the results of including petroleum refining

As Fig. 2 showed, refining accounts for 7–25% of manufacturing emissions when included as a branch of manufacturing. In Paper 1, we analyzed difficulties associated with calculating energy consumption and output data in petroleum refining. We showed that inclusion of petroleum refining does not have a significant impact on the overall trends in energy consumption, intensity and structure in manufacturing. However, due to its importance in total emissions, it is essential to assess the effect of including petroleum refining in the analysis of carbon emissions from manufacturing.

The results in Table 4 show that the impact from incorporating carbon emissions from petroleum refining into our analysis of trends in manufacturing carbon emissions is negligible for most countries. The average annual rates of change in carbon emissions and the effects of activity, structure, intensity, fuel mix and primary utility mix shift very little when carbon emissions from petroleum refining are included in the analysis. The most

[21] See subsequent section on pre- and post-1990 trends in carbon emissions.

Table 4
Effects from including refining on the average annual rates of change in carbon emission factors[a]

	Manufacturing with refining							Difference between with and without refining results						
	Actual (%)	Activity effect (%)	Structure effect (%)	Carbon intensity (%)	Energy intensity (%)	Final fuel mix (%)	Primary utility (%)	Actual (%)	Activity effect (%)	Structure effect (%)	Carbon intensity (%)	Energy intensity (%)	Final fuel mix (%)	Primary utility (%)
Australia	1.0	2.5	0.1	−1.4	−1.7	0.4	−0.3	−0.2	0.0	0.0	−0.2	−0.2	0.0	0.0
Canada	−0.6	1.5	−0.4	−2.0	−1.1	−0.3	−0.2	0.0	0.0	−0.2	0.0	0.1	0.1	0.1
Denmark	−1.2	1.5	−0.5	−2.6	−1.5	−1.0	0.4	0.3	0.0	−0.2	0.3	0.3	0.2	−0.1
Finland	0.0	2.7	0.3	−2.7	−2.0	−1.0	−0.2	0.1	0.0	0.0	−0.1	−0.2	−0.1	0.0
France	−3.0	1.1	−0.3	−4.1	−2.0	−0.1	−1.8	0.2	−0.2	−0.1	0.4	0.3	0.1	0.2
W. Germany	−1.7	0.9	−0.2	−2.6	−1.7	0.4	−1.1	0.0	−0.1	−0.1	0.1	0.2	0.0	0.1
Italy	−0.2	2.9	0.2	−3.2	−3.6	0.2	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0
Japan	−0.7	3.0	−1.3	−3.7	−2.2	0.4	−0.7	0.1	0.0	−0.1	0.1	0.2	0.0	0.0
Netherlands	−2.8	1.7	0.3	−4.5	−4.9	−0.1	0.2	0.6	0.0	−0.3	0.6	0.9	0.0	0.0
Norway	−0.2	0.5	1.5	−0.7	−1.1	−1.1	0.0	1.2	0.0	1.1	1.2	0.1	0.1	0.0
Sweden	−3.2	1.3	0.3	−4.5	−2.3	−1.7	−0.9	0.9	0.0	0.3	0.9	0.3	0.2	0.1
UK	−2.7	0.3	−0.3	−2.9	−2.4	0.7	−0.9	0.3	0.0	0.0	0.3	0.2	−0.1	0.1
US	−0.6	2.1	−0.9	−2.7	−1.5	0.1	−0.3	−0.1	0.0	−0.1	−0.1	−0.1	0.0	0.1

[a] Note: There is some disparity in the differences for the Denmark results because the figures were recalculated starting from 1975 due to missing refining data.

Table 5
Effects from including refining on manufacturing carbon emissions and aggregate carbon intensity

Country	Carbon emissions		Carbon intensity	
	1973 (%)	1994 (%)	1973 (%)	1994 (%)
Australia	12	10	9	6
Canada	25	26	24	24
Denmark	1	11	0	10
Finland	13	10	10	7
France	14	19	3	12
W. Germany	12	12	6	8
Italy	11	12	10	11
Japan	8	10	6	9
Netherlands	24	27	14	18
Norway	3	33	3	32
Sweden	5	27	4	25
UK	11	17	9	15
US	24	22	21	20

notable changes in emissions growth occur in Norway and Sweden, the two countries with the greatest relative expansion in refining output.

Including refining in our Mine/Yours analysis changes results in five countries (see Fig. 4). Including refining reduces the share of energy-intensive sectors below the average in the IEA-13 structure in Japan, and increases this share in France. In Norway this increases carbon intensity of manufacturing above the average, while reducing it in Netherlands. In Denmark, the IEA-13 adjustment reduces primary utility mix below the average of the IEA-13 utility mix. However, inclusion of carbon emissions from petroleum refining has the most pronounced effect on absolute values of manufacturing carbon emissions and carbon intensity. Accounting emissions from petroleum refining is especially important in the case of Norway, Sweden, Netherlands, Canada and the US (see Table 5).

We conclude that emissions from refining significantly alter the AWD decomposition results for only two IEA-13 countries. But they have an important impact on total emissions and emissions intensity in all of them. Therefore, it is important to include petroleum refining in the estimate of carbon emissions from manufacturing to accurately assess each country's industrial emissions.

5.2. Other industries

We have aggregated three non-manufacturing industries — mining (which includes extraction of energy resources), agriculture (which includes fishing and forestry), and construction — into a sector called "other industries". These industries are often not included in international comparisons of energy use and carbon emissions. They have not been included in our previous studies because data for several countries are incomplete or unreliable. For this reason we have had to exclude West Germany, Netherlands, Canada, and Norway from our analysis of trends from 1973. We refer to the sample of remaining countries as the IEA-9.

If these industries were included with manufacturing as part of "industry" (not including refining) they would comprise 32% of IEA-9 total industrial value added, and almost 20% of IEA-9 industrial carbon emissions (see Fig. 8). The difference in the shares of output and emissions indicates that on average other industries are considerably less carbon-intensive than manufacturing. With other industries included in manufacturing, aggregate industry carbon intensity falls nearly 20%. However, including these industries has the effect of slowing down the rate of decline of industry carbon intensity. As Fig. 8 shows, while the share of other industries output in IEA-9 total industry has fallen, their share of carbon emissions has increased. These seemingly contradictory trends are explained by the fact that carbon intensity has declined much more rapidly in manufacturing than it has in other industries (45% decrease in IEA-9 carbon intensity from 1973 to 1994 for manufacturing versus 14% for other industries).

Fig. 8 also shows that total emissions from this sector have increased only marginally over the study period. Partly this is due to the relatively slow growth of the sector. Total output in 1983 was slightly less than 1973 levels. The strong growth from 1983 to 1990 stems mostly from a construction boom during that time. The narrowing gap between emissions and activity from 1978 to 1986 indicates the falling carbon intensity that characterized this period.

The aggregate carbon intensities of other industries in 1973 (or the first year in which complete data are available) and 1994 are depicted in Fig. 9. The sections of the bars represent the shares of emissions originating in each subsector. Construction actually contributes well over half of the value added from this sector, but it is far less carbon-intensive than agriculture and mining. Agriculture contributed the largest amount of carbon emissions from fuel consumption in most countries. However, agriculture is less carbon-intensive on average than mining.[22] The importance of the mining industry in determining aggregate carbon intensity depends not only on the size but also on the composition of the mining industry in the country. Mining comprised 22–32% of the 1994 other industries' GDP in Australia, Canada, Netherlands, the UK, and the US, but the mining emissions share varies widely, as Fig. 9 shows. Although we have not been able to analyze the differences in energy intensities for the extraction of different types of mining products, it would appear that the enormous differences in the contributions

[22] We provide a detailed analysis of trends in energy consumption and carbon emissions in agriculture, mining and construction in a separate study (Murtishaw *et al*., 2000).

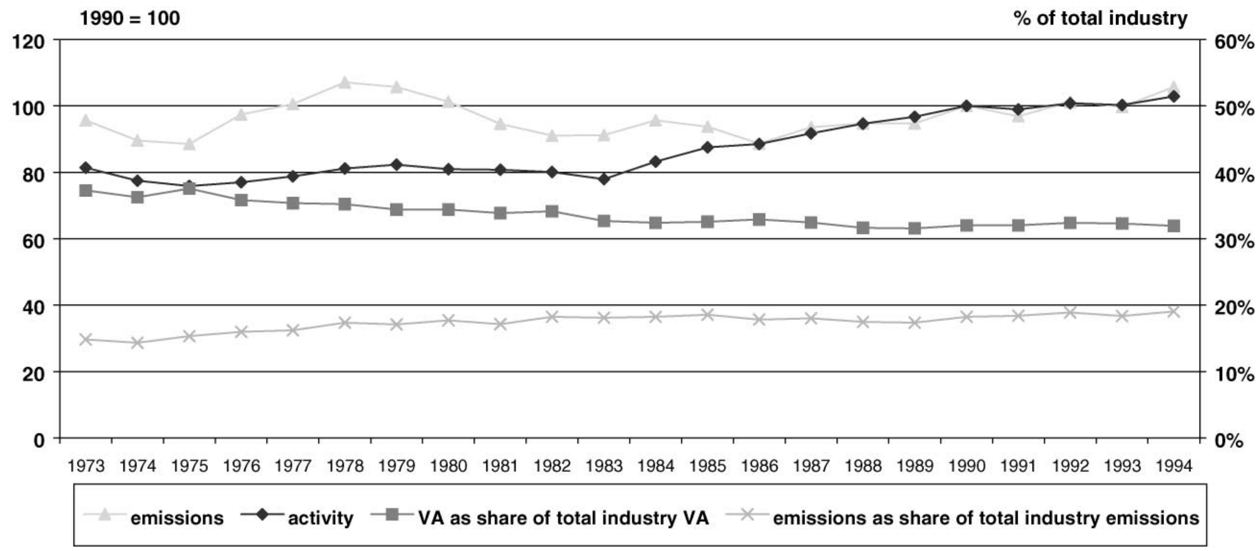


Fig. 8. IEA-8 other industries value added and emissions trends, and as share of total industrial sector.

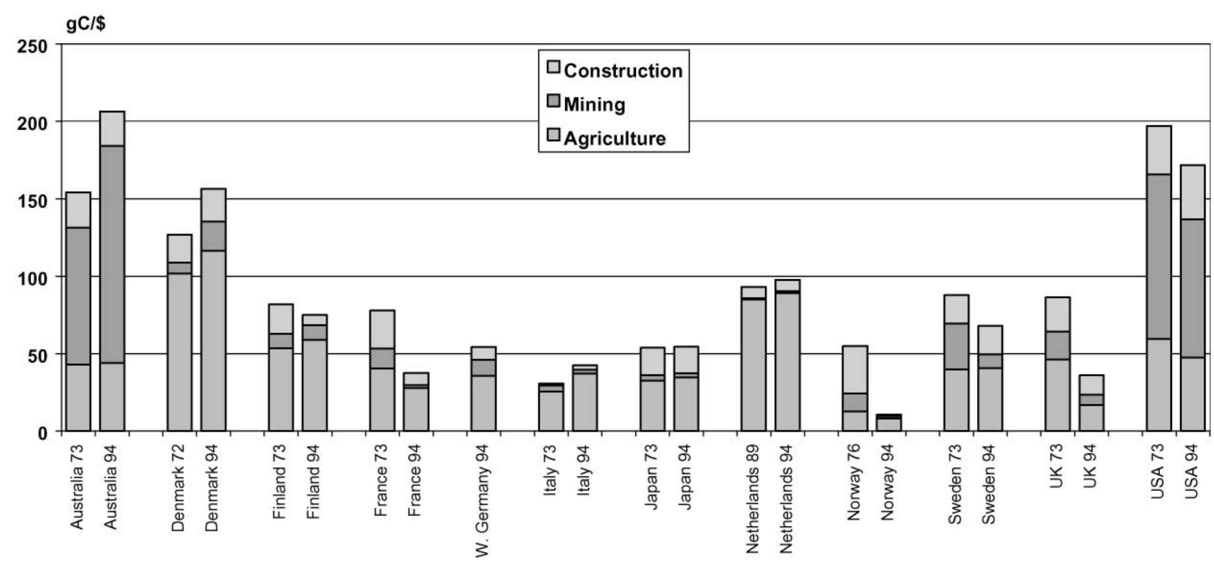


Fig. 9. Other industries carbon emissions per value added by subsectoral shares of emissions. Note: Carbon intensity for Italy in 1973 is slightly overestimated due to missing data for mining value added.

to emissions shares stem from a much higher energy intensity associated with hardrock mining compared to petroleum and gas extraction.

Some countries have experienced significant declines in other industries carbon intensity. One disturbing trend is that carbon intensity increased in four countries, most noticeably in Australia. In Denmark, the figure has fluctuated around the mean carbon intensity so the trend has not been consistent, and in Netherlands the complete time series is too short to draw firm conclusions. This is not true, however, for Italy and Australia. In Australia steadily increasing carbon intensity in the mining industry has driven up the aggregate intensity, while in Italy carbon intensity increased in both agriculture and construction. We are not sure why carbon intensity has increased in these countries. Declining prices of commodities on the world market has certainly acted to increase the carbon intensity of agriculture and mining in all countries. To some extent the increases in Italy and Australia could result from structural changes at the subsectoral level, such as a shift in the shares of commodities produced. It may also in part be the product of more accurate reporting of energy consumption or changes in estimation methodology.

The impacts of output growth and changes in aggregate carbon intensity are displayed in Fig. 10. One striking

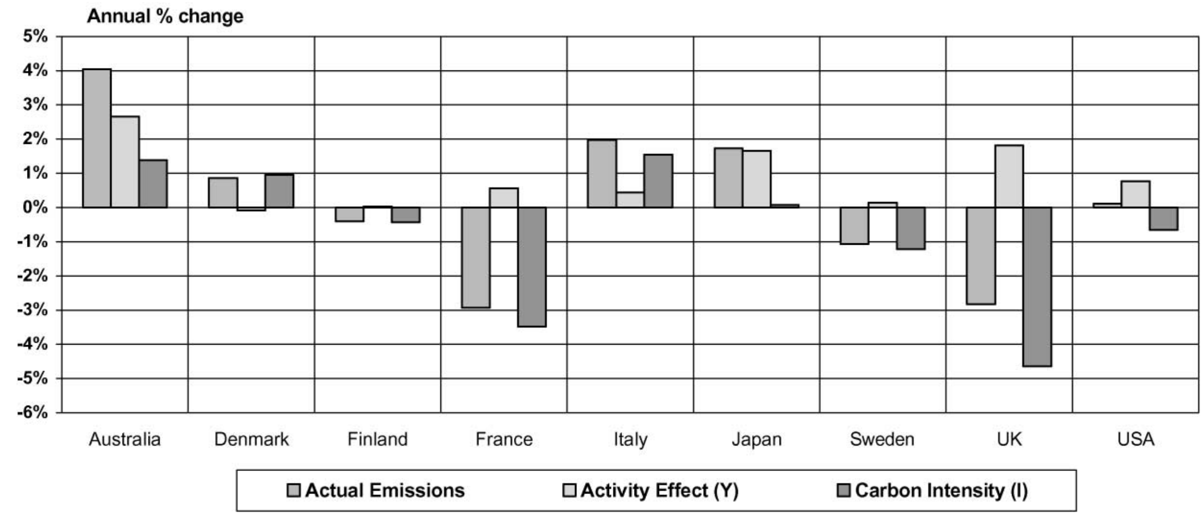


Fig. 10. Decomposition effects for IEA-9 carbon emissions, actual, activity, and carbon intensity effects, 1973–1994.

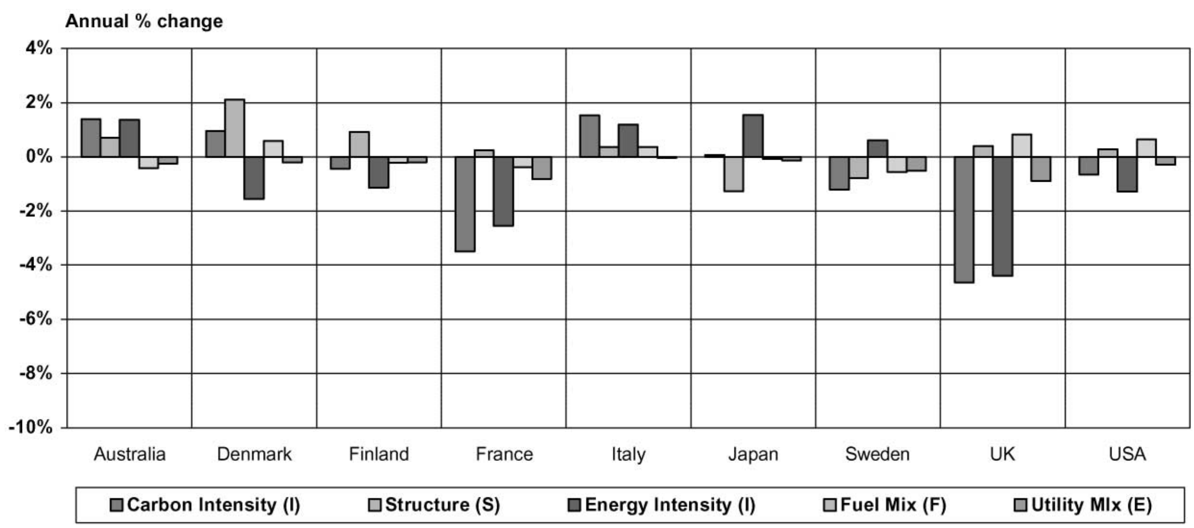


Fig. 11. Components of changes in aggregate carbon intensity, 1973–1994.

characteristic of this sector is its extremely low rate of growth. Only three IEA-9 countries experienced annual growth rates greater than 1% in this sector. In the UK, strong growth was offset by sizeable reductions in carbon intensity. This is due largely to the fact that petroleum extraction superseded coal mining as a significant contribution to output in the sector, but the UK has also accomplished steady decreases in the carbon intensity of agriculture. The carbon intensity of Australia's other industries increased in conjunction with vigorous sectoral growth, resulting in an alarming increase in emissions. In contrast to the manufacturing industries, no consistent trends emerge in either activity or carbon intensity among the IEA-9.

Fig. 11 breaks down the changes in aggregate carbon intensity into its decomposition terms. Energy intensity is by far the most important determinant of the changes in carbon intensity. Energy intensity actually increased in four of the IEA-9 countries. Decreasing energy intensity played the biggest role in the large reductions in carbon intensity in France and the UK, while increasing energy intensities were a significant factor pushing carbon intensity up in Australia and Italy.

Structural changes exerted upward pressure on emissions for all countries but Japan and Sweden. Japan, which experienced the greatest degree of structural change, was the country in which construction value-added grew the most and the only country where the value-added by construction grew while mining and agriculture both declined. In six countries the real output per capita of construction declined, which is largely

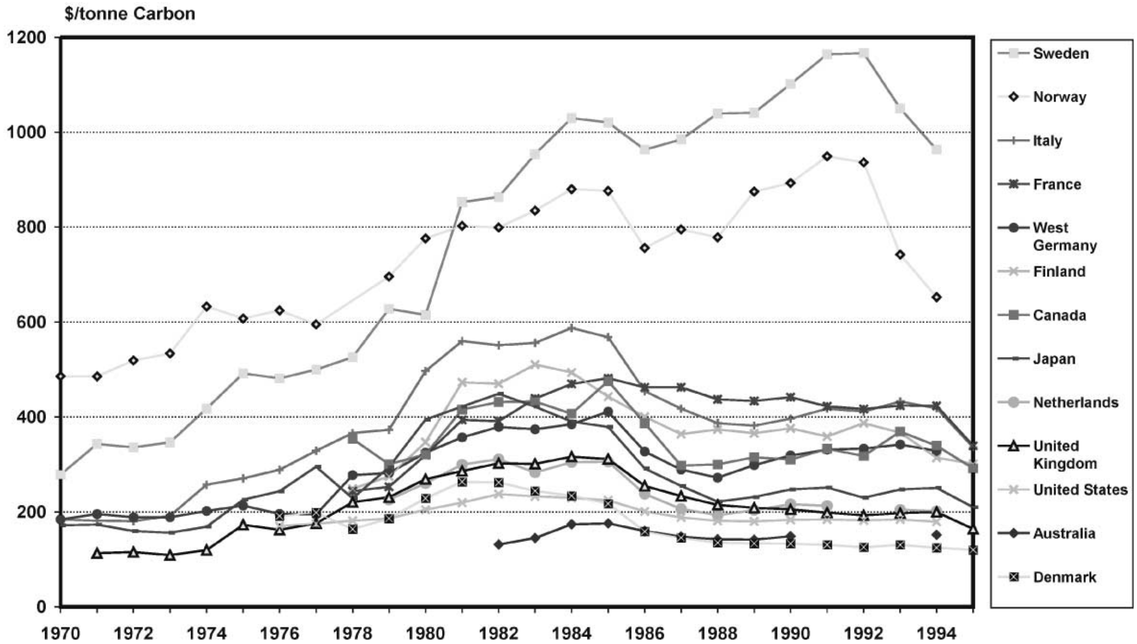


Fig. 12. Price of carbon in manufacturing.

responsible for the structural trend toward greater energy consumption. Sweden's declining structure effect results from the diminished output from mining, which is by far the most energy-intensive of the other industries in Sweden. The UK is an interesting case. It had the largest reduction in carbon intensity while simultaneously having the second highest growth rate in this sector.

Among the IEA-9 changes in fuel mix had varied effects. In Denmark, the US, the UK, and Italy fuel switching boosted emissions from 8 to 19%. The other five countries benefited from modest decreases in emissions from this effect. On average, oil and coal shares in delivered energy remained remarkably constant. Electricity's share grew from 22 to 28%. This increase came almost entirely at the expense of a commensurate decline in the use of natural gas over the study period, principally between 1976 and 1986. However, natural gas consumption began to rebound after 1986, increasing at an average annual rate of 6.6% to 1994. The mining industries in Australia and the US, where gas use increased sharply over this period, were the main drivers of this increase. Natural gas played a significant part in holding down emissions from these two countries. In Australia, natural gas use increased at a much faster rate than other fuels, which explains the negative final fuel effect there. In Japan, oil consumption increased over 50% while electricity use remained relatively stagnant, growing only 12%. Since electricity constitutes a considerably smaller share of energy use in other industries than in manufacturing, the utility mix effect is less important, although it did play some role in restraining emissions in France and the UK.

Other industries contribute a significant part to total industrial output and carbon emissions. More importantly the contribution of those industries to total industrial carbon emissions is growing, despite the falling share of output. We conclude that more attention should be paid to energy and carbon emissions trends in other industries, and measures should be taken to reduce carbon intensities in those industries.

6. Causes of changes in emissions

Naturally, questions arise concerning the causes for the observed changes in output, energy use, and carbon emissions. In Paper 1 we noted that both changes in energy prices and long-term changes in technology were the principle causes of changes in energy intensities. The latter's importance is supported by the decline in energy intensities that took place in most countries even before the first oil price shock.

A full analysis of those causes is beyond the scope of this paper, but we can comment on possible reasons for what we observed. Fig. 12 shows the "price of carbon" for each of the IEA-13 countries. We calculated this by weighting fuel prices by carbon content of fuels. Some approximations were made for oil products where light oil prices were not available, but the trends shown give a fair representation of what it cost to "buy" carbon. For utilities the average carbon content of a kWh or unit of purchased heat was used.

The increase in oil prices after the first and second oil price shock pushed up the price of carbon. Declining oil

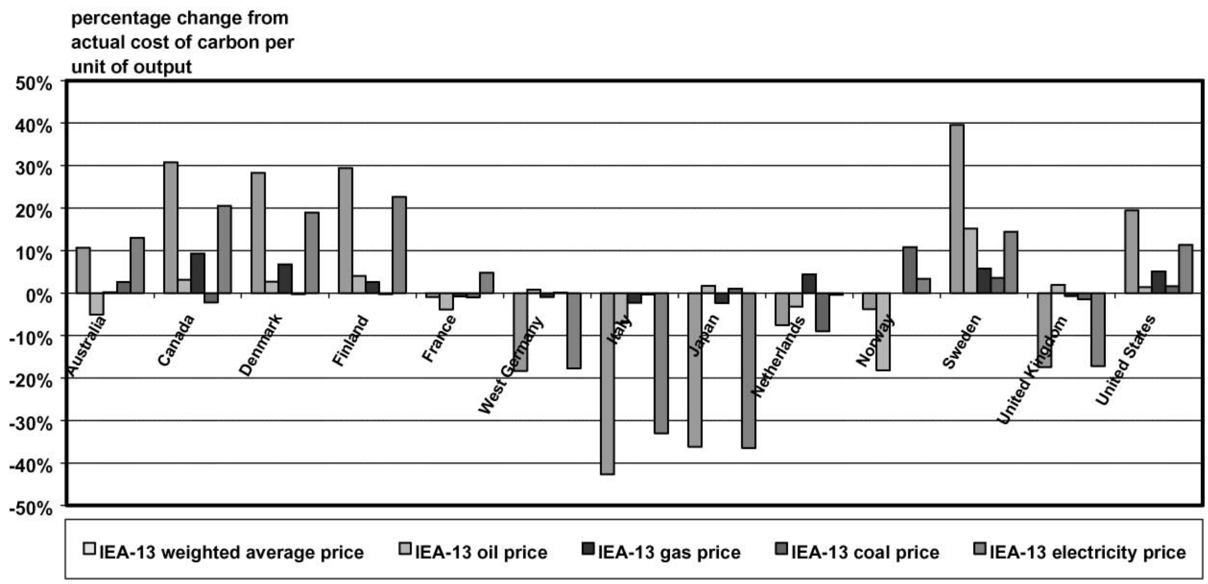


Fig. 13. Changes in countries cost of carbon per unit of output with substitution for IEA-13 fuel prices, weighted average and by fuel.

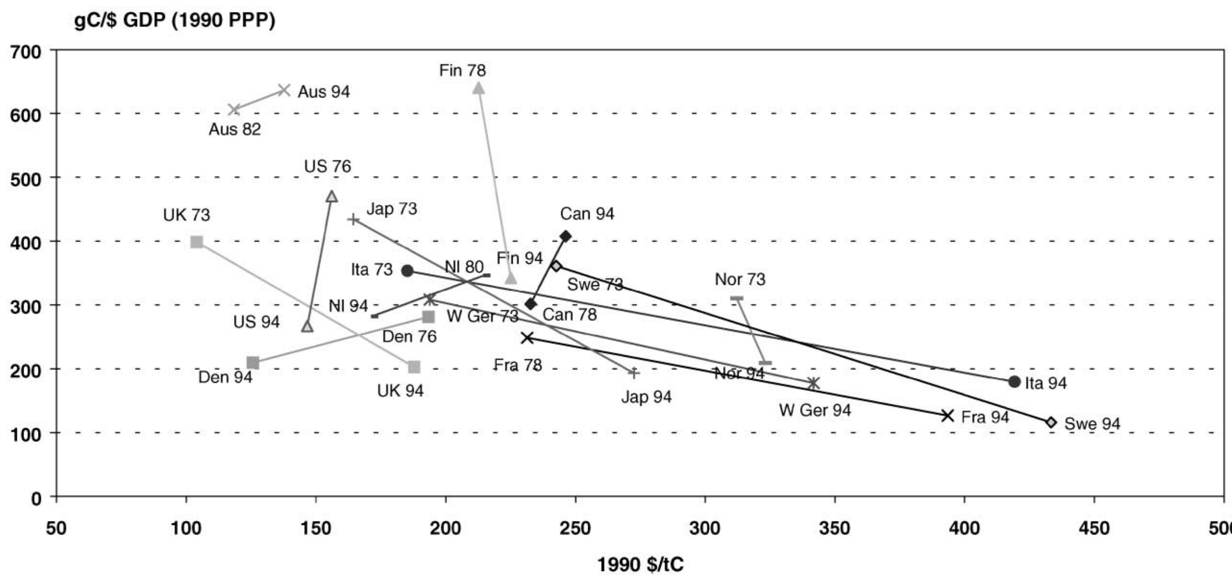


Fig. 14. Carbon intensities vs. avg. weighted price of carbon.

prices in the mid-1980s should have brought a reduction in the price of carbon. However, as industries moved from oil to gas, they emitted less carbon per unit of energy cost. At the same time the increasing share of electricity also pushed up the weighted-average price of carbon for some countries.

In order to analyze the differences in the costs of carbon per unit of output among the countries we calculate the IEA-13 price averages for each of the main fuels and electricity and the IEA-13 weighted-average fuel price. Further we substitute each country's fuel price by the respective IEA-13 averages, and compare the resulting cost of carbon per unit of output with the actual. The results presented in Fig. 13 show how the substitution of fuel prices will change the actual cost of carbon per unit of manufacturing output. It can be observed that in Italy, Japan, West Germany, the UK and Netherlands, the cost of carbon would be much lower if those countries had to pay IEA-13 weighted-average price for fuels. This is mainly due to a higher price of electricity in these countries compared to the IEA-13 average, and the higher price of coal in Netherlands. On the other hand, with IEA-13 weighted-average prices the cost of carbon per unit of output

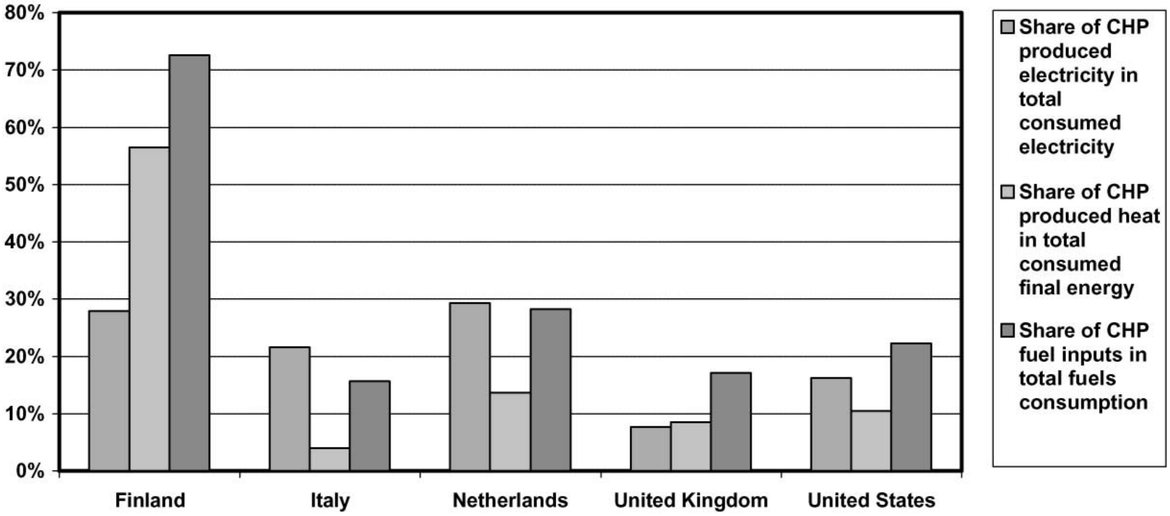


Fig. 15. Share of industrial CHP in manufacturing electricity production and fuels consumption.

would be significantly higher in Sweden, Canada, Finland, Denmark, the US, and Australia. In countries such as France and Norway fuel price substitution does not noticeably change the actual cost of carbon per unit of output. In France and Norway the low-carbon content electricity compensates for the increase in price from IEA-13 electricity price substitution.

Fig. 14 portrays this relationship in another way. We show aggregate carbon intensity on the vertical axis, vs. the price of carbon on the horizontal axis. The first and last year for which we have data for each country is shown. All countries but Australia show lower carbon intensity in the final year compared with the first year. Most show higher carbon prices in the most recent year than in the first year as well. But there are some notable exceptions, particularly the US and Sweden, where real prices for many energy sources fell after 1986. The figure suggests strongly but does not quantify an important elasticity of carbon intensity with respect to the price of carbon. That some countries wound up with lower- price carbon and significantly lower carbon intensity can be explained by the work of Walker and Wirl (1993), which points to the irreversibility of many energy-efficiency improvements, which persist even if fuel prices fall. Furthermore, we would add that the incentive to switch from coal or oil to natural gas, which reduces carbon intensity, is strong even when prices are low because of the environmental benefits of using gas. But exactly how much a future rise in the price of carbon would drive down carbon intensity is still a matter of some debate.

Another cause behind the reductions in manufacturing primary energy intensity in several countries was the increase in combined heat and power (CHP) systems in industry. CHP systems that generate electrical/mechanical and thermal energy simultaneously at an industrial site in many cases will provide a more efficient use of input fuels than conventional separate production of heat and electricity, with overall efficiency of up to 85%. In the last two decades the benefits of CHP systems have been introduced in industry in all of the IEA-13 countries, except Norway. However, due to institutional, regulatory and economic barriers, the penetration of CHP technologies in most countries is small. Fig. 15 shows the share of electricity generated by CHP systems in total electricity consumed in manufacturing, and the share of heat produced by CHP in delivered energy consumed in several countries.[23] It also shows the respective fuel consumption of CHP systems in total fuel consumption in manufacturing.

Despite the obvious benefits for primary energy savings, CHP systems may not always contribute to aggregate carbon emissions reductions. We estimated the amount of energy inputs needed by conventional industrial boilers and conventional power generating systems to produce the same amount of heat and electricity that was produced by CHP systems in manufacturing in several countries in 1994. Further, we estimated the amount of carbon emissions that would be emitted by conventional heat and power generation systems if they produced the same amount of heat and electricity that was produced in 1994 by industrial CHP systems. The results are presented in Fig. 16. In all the countries primary energy intensity would have been higher, if no industrial CHP systems were employed in manufacturing. However, the effect on carbon emissions of the CHP systems is mixed. While Finland, Italy, and the US saved on carbon emissions through installation of CHP systems, the UK and Netherlands have increased their emissions through

[23] Reliable, IEA-wide statistics on industrial CHP systems do not exist. Industrial CHP in Norway is negligible.

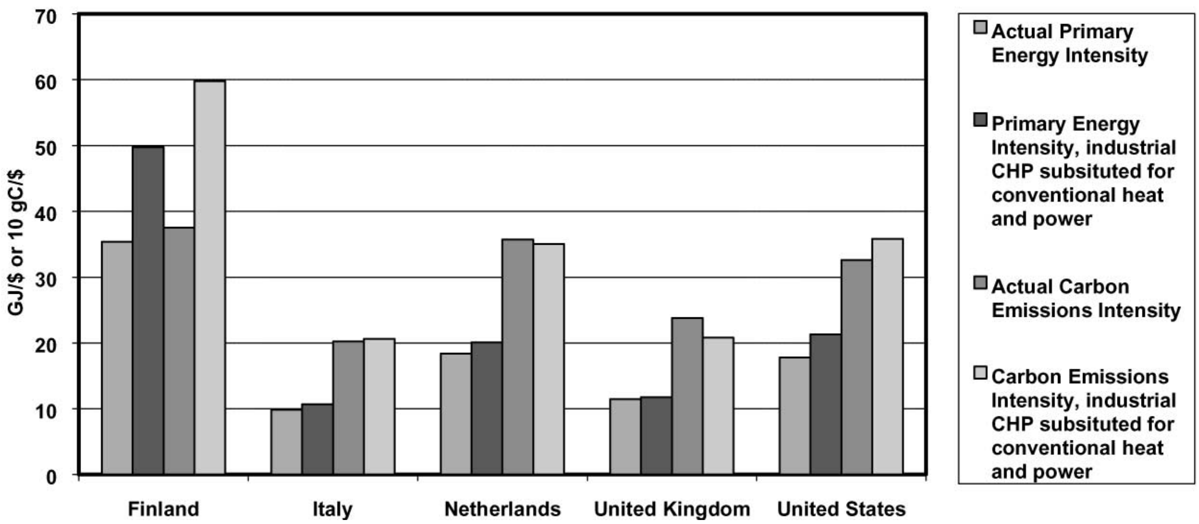


Fig. 16. Benefits of CHP systems for primary energy intensity and carbon emissions intensity reduction.

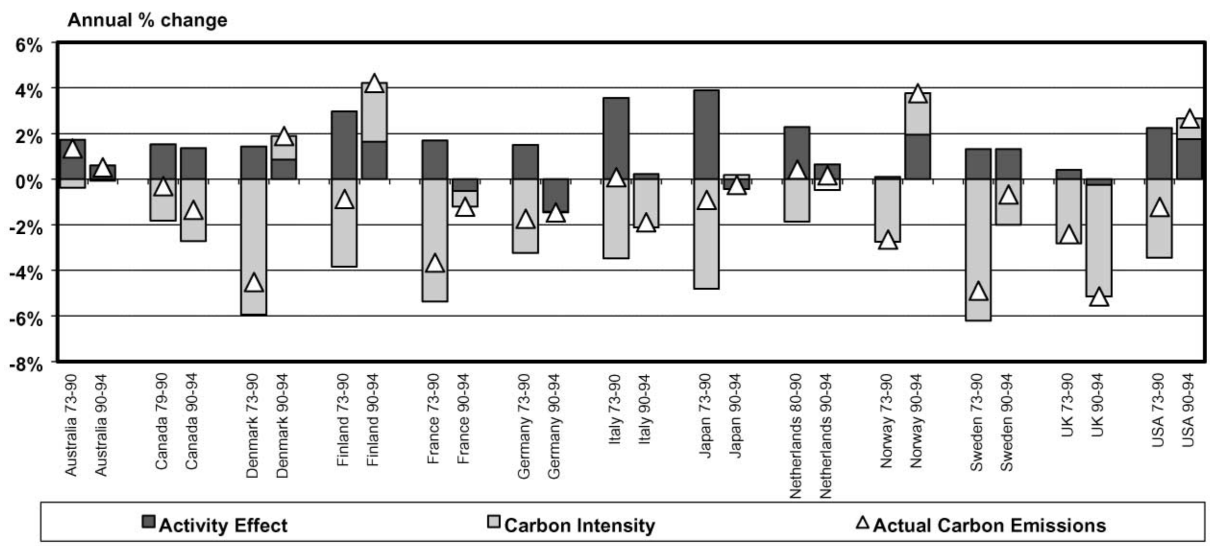


Fig. 17. Average annual percentage change of actual emissions, activity, and carbon intensity effects, 1973–1990 vs. 1990–1994.

CHP installations. The reason is that over the years utilities' fuel mix became less carbon-intensive, due to the higher use of gas and renewables, while CHP systems were installed mostly at industrial facilities with high heat requirements, often using carbon-intensive fuels for their thermal needs. Therefore, new incremental CHP capacities that come online should be based on low-carbon fuels in order to realize the full benefits of these technologies in terms of carbon emissions reductions.

7. Comparison of post- and pre-1990 trends

Some trends in the early 1990s should be of special concern to policy makers. First, the gap between annual growth rates in energy use and output has declined in most of the countries in the early 1990s compared to the previous period. Second, the rate of decline in delivered energy intensities slowed down in three and reversed in four of the IEA-13 countries in the 1990s. Third, the annual growth rate of electricity consumption slowed down in most countries, but electricity intensity grew more rapidly in the 1990s in eight IEA-13 countries (six of which have a relatively fossil fuel-intensive utility mix).

Fig. 17 shows the difference between the average annual growth rates in actual carbon emissions and the effects of activity and aggregate carbon intensity in the early 1990s vs. the period from 1973 to 1990. The recession of the early 1990s is evident in the steep drop in activity for several countries. However, the decline in

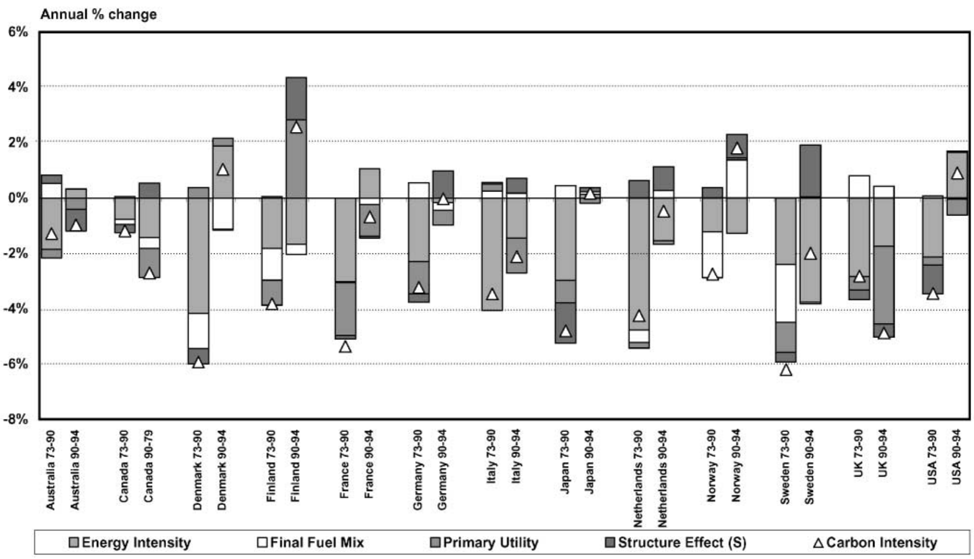


Fig. 18. Average annual percentage change of carbon intensity, structure, energy intensity, final fuel mix, and utility mix effects of carbon emissions, 1973–1990 vs. 1990–1994.

actual carbon emissions has slowed down in four countries and reversed in five others. The rate of change of carbon intensity increased in 11 countries, by 4% or more in most of them. In Norway increases in both the activity effect and carbon intensity reversed the previous trend of declining emissions. Falling output was sufficient to reduce emissions in Italy despite the slowing carbon intensity decline. Only in the UK and Canada did the rate of change of carbon intensity fall further.

Fig. 18 offers more insight into what caused the carbon intensity rates of change to increase in the 1990s. In eight of the IEA-13 countries the slowdown or reversal of carbon intensity results mostly from increases in the change in energy intensity. The increasing energy intensities are not so surprising in light of the recession. Energy intensity often increases appreciably during recessionary periods due to the suboptimal capacity utilization that occurs as production declines. Increasing carbon intensity in the primary utility mix was the main factor in Finland. This factor also helped to increase carbon intensity rates in four other countries. The final fuel mix was important only in Norway and Sweden.

8. Conclusions

Overall, emissions from manufacturing in 1994 were below their 1973 levels in most of the countries studied. Growth in output was the main factor pushing carbon emissions up, while improved energy efficiency was the largest factor compensating for this growth. Changes in the primary utility mix also contributed to the reduction of carbon emissions, while changes in structure and final fuel mix had a mixed effect on aggregate emissions among countries.

Including refining as a branch in our manufacturing data does not significantly alter the AWD decomposition results, except for Norway and Sweden where growth in refining output far surpassed the other IEA-13 countries. However, since refining is on average the most carbon-intensive industry, its emissions dramatically increase the aggregate carbon intensity of manufacturing in most countries. Refining carbon intensity has also fallen more slowly than in any other manufacturing branch, which indicates that it may be an important target for future emissions reductions.

Other industries, which on average are much less carbon-intensive than manufacturing, still account for about a fifth of total industrial emissions. As with refining, little progress has been achieved in decreasing carbon intensity in this sector, and as a result its share of industrial emissions has been growing, despite a falling share of value added.

In this paper we have also used a novel comparative technique we refer to as Mine/Yours analysis, which permits a decomposition of the differences in emissions for a given year into the underlying components. We found that aggregate carbon intensity accounts for slightly more of the variation in actual emissions than do differences in per capita value added. Energy intensity and utility fuel mix together explain most of the variation in aggregate carbon intensity, while structure and final fuel mix account for surprisingly little.

National authorities correctly recognize the principal factors that have historically driven the trends in energy use and carbon emissions. In their National Communications to the UNFCCC they anticipate that these factors will continue to reduce emissions further in the future. Therefore, the changes in the trends concerning these factors in the 1990s should be of special concern to policy makers. That energy prices are more stable today than in the 1970s/1980s is one reason why factors formerly restraining emissions are weaker today. Additionally, we may be reaching saturation of some decarbonization components, such as increases in the share of nuclear or hydro-power, or the substitution of coal and oil with gas. However, many available energy-saving technologies have yet to penetrate thoroughly the existing capital stock, and other emerging technologies promise to reduce markedly energy intensities in some industries (de Beer *et al.*, 1997, 1998; World Energy Council, 1995). How rapidly these new technologies can be brought on line is uncertain, and whether the voluntary agreements in effect in many countries will actually reduce emissions intensities more rapidly than output growth remains doubtful.

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Appendix A. Mathematical derivation of the AWD method

Total carbon emissions can be defined as the product of activity, carbon intensity of each fuel, share of each fuel in the total fuel mix, energy intensity of each end use, and share of each end use in the total activity mix (summed over all end uses and fuels). That relationship is defined as follows:

$$C_t = \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t \frac{C_{ijt}}{E_{ijt}}\frac{E_{ijt}}{E_{it}}\frac{E_{it}}{Y_{it}}\frac{Y_{it}}{Y_t} = \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t R_{ijt} e_{jt} I_{it} y_{it}. \tag{A.1}$$

Differentiating with respect to time results in

$$\frac{\partial C_t}{\partial t} = \frac{\partial Y_t}{\partial t}\frac{C_t}{Y_t} + \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t \frac{\partial R_{ijt}}{\partial t} e_{jt} I_{it} y_{it} + \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t R_{ijt}\frac{\partial e_{jt}}{\partial t} I_{it} y_{it} + \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t R_{ijt} e_{jt}\frac{\partial I_{it}}{\partial t} y_{it} + \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t R_{ijt} e_{jt} I_{it}\frac{\partial y_{it}}{\partial t}. \tag{A.2}$$

Dividing by C_t and integrating from 0 to T:

$$\ln\left(\frac{C_t}{C_0}\right) = \int_0^T \frac{\partial Y_t}{\partial t}\frac{\mathrm{d}t}{Y_t} + \int_0^T \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t \frac{\partial R_{ijt}}{\partial t}\frac{e_{jt} I_{it} y_{it}}{C_t}\,\mathrm{d}t + \int_0^T \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t \frac{\partial e_{jt}}{\partial t}\frac{R_{ijt} I_{it} y_{it}}{C_t}\,\mathrm{d}t + \int_0^T \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t \frac{\partial y_{it}}{\partial t}\frac{R_{ijt} I_{it} e_{jt}}{C_t}\,\mathrm{d}t + \int_0^T \sum_{i=1}^{m}\sum_{j=1}^{n} Y_t \frac{\partial I_{it}}{\partial t}\frac{R_{ijt} e_{jt} y_{it}}{C_t}\,\mathrm{d}t. \tag{A.3}$$

Both parametric methods (Laspeyres and AWD) rely on this decomposition, differing only in how they parameterize the integrals, and require the following assumptions on the paths of the components of the integrals:

$$\begin{aligned}
&\min\{R_{ij0}, R_{ijt}\} \leqslant R_{ij\tau} \leqslant \max\{R_{ij0}, R_{ijt}\}, \text{where} \\
&\min\{e_{j0}, e_{jt}\} \leqslant e_{j\tau} \leqslant \max\{e_{j0}, e_{jt}\}, \\
&\min\{I_{i0}, I_{it}\} \leqslant I_{i\tau} \leqslant \max\{I_{i0}, I_{it}\}, \\
&\min\{y_{i0}, y_{it}\} \leqslant y_{i\tau} \leqslant \max\{y_{i0}, y_{it}\}, \\
&\text{where} \\
&0 \leqslant \tau \leqslant t.
\end{aligned}$$

A discrete parameterization of Eq. (A.3) yields the following:

$$\ln\left(\frac{C_t}{C_0}\right) = \ln\left(\frac{Y_t}{Y_0}\right) + \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{Y_0 y_{i0} e_{j0} I_{i0}}{C_0} + \alpha_{itj}\left(\frac{Y_t y_{it} e_{jt} I_{it}}{C_t} - \frac{Y_0 y_{i0} e_{j0} I_{i0}}{C_0}\right)\right)\Delta R_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{Y_0 R_{ij0} I_{i0} y_{i0}}{C_0} + \beta_{ijt}\left(\frac{Y_t R_{ijt} I_{it} y_{it}}{C_t} - \frac{Y_0 R_{ij0} I_{i0} y_{i0}}{C_0}\right)\right)\Delta e_{ij} + \sum_{i=1}^{m}\left(\frac{Y_0 R_{i0} y_{i0}}{C_0}\right.$$

$$+\gamma_{it}\left(\frac{Y_t R_{it} y_{it}}{C_t}-\frac{Y_0 R_{i0} y_{i0}}{C_0}\right)\Bigg)\Delta I_i$$
$$+\sum_{i=1}^{m}\left(\frac{Y_0 R_{i0} I_{i0}}{C_0}\right.$$
$$\left.+\omega_{it}\left(\frac{Y_t R_{it} I_{it}}{C_t}-\frac{Y_0 R_{i0} I_{i0}}{C_0}\right)\right)\Delta y_i.$$

Simplifying and exponentiating Eq. (A.3) results in an index decomposition that describes changes in total carbon emissions as follows:

$$\begin{aligned}(1+\Delta\%C_{\text{tot}})_{0t} &= \exp\left[\ln\left(\frac{Y_t}{Y_0}\right)\right]\\
&\times\exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{c_{ij0}}{R_{ij0}}+\alpha_{itj}\left(\frac{c_{ijt}}{R_{ijt}}-\frac{c_{ij0}}{R_{ij0}}\right)\right)\Delta R_{ij}\right]\\
&\times\exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{c_{ij0}}{e_{j0}}+\beta_{ijt}\left(\frac{c_{ijt}}{e_{jt}}-\frac{c_{ij0}}{e_{j0}}\right)\right)\Delta e_j\right]\\
&\times\exp\left[\sum_{i=1}^{m}\left(\frac{c_{i0}}{I_{i0}}+\gamma_{it}\left(\frac{c_{it}}{I_{it}}-\frac{c_{i0}}{I_{i0}}\right)\right)\Delta I_i\right]\\
&\times\exp\left[\sum_{i=1}^{m}\left(\frac{c_{i0}}{y_{i0}}+\omega_{it}\left(\frac{c_{it}}{y_{it}}-\frac{c_{i0}}{y_{i0}}\right)\right)\Delta y_i\right],\end{aligned}$$

where the multiplicative terms are $(1+\%\Delta C_{\text{emissions}})_{0t}$, $(1+\%\Delta C_{\text{fuelmix}})_{0t}$, $(1+\%\Delta C_{\text{fuelmix}})_{0t}$, $(1+\%\Delta C_{\text{intensity}})_{0t}$, and $(1+\%\Delta C_{\text{structure}})_{0t}$, respectively. The continuous parameterization requires simplifying Eq. (A.3) as follows:

$$\begin{aligned}\ln\left(\frac{C_t}{C_0}\right) &= \int_0^T\frac{\partial Y_t}{\partial t}\frac{\mathrm{d}t}{Y_t}+\int_0^T\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{\partial R_{ijt}}{\partial t}\frac{c_{ijt}}{R_{ijt}}\,\mathrm{d}t\\
&+\int_0^T\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{\partial e_{jt}}{\partial t}\frac{c_{ijt}}{e_{jt}}\,\mathrm{d}t\\
&+\int_0^T\sum_{i=1}^{m}\frac{\partial I_{it}}{\partial t}\frac{c_{it}}{I_{it}}\,\mathrm{d}t\\
&+\int_0^T\sum_{i=1}^{m}\frac{\partial y_{it}}{\partial t}\frac{c_{it}}{y_{it}}\,\mathrm{d}t.\end{aligned}$$

The continuous parameterization then yields:

$$\begin{aligned}\ln\left(\frac{C_t}{C_0}\right) &= \ln\left(\frac{Y_t}{Y_0}\right)+\sum_{i=1}^{m}\sum_{j=1}^{n}(c_{ij0}+\alpha_{ijt}\Delta c_{ij})\ln\left(\frac{R_{ijt}}{R_{ij0}}\right)\\
&+\sum_{i=1}^{m}\sum_{j=1}^{n}(c_{ij0}+\beta_{ijt}\Delta c_{ij})\ln\left(\frac{e_{jt}}{e_{j0}}\right)\\
&+\sum_{i=1}^{m}(c_{i0}+\gamma_{it}\Delta c_i)\ln\left(\frac{I_{it}}{I_{i0}}\right)\\
&+\sum_{i=1}^{m}(c_{i0}+\omega_{it}\Delta c_i)\ln\left(\frac{y_{it}}{y_{i0}}\right).\end{aligned}$$

Exponentiating results in an index decomposition that describes changes in total carbon emissions from as follows:

$$\begin{aligned}(1+\%\Delta C_{\text{tot}})_{0t} &= \exp\left[\ln\left(\frac{Y_t}{Y_0}\right)\right]\\
&\times\exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}(c_{ij0}+\alpha_{ijt}\Delta c_{ij})\ln\left(\frac{R_{ijt}}{R_{ij0}}\right)\right]\\
&\times\exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}(c_{ij0}+\beta_{ijt}\Delta c_{ij})\ln\left(\frac{e_{jt}}{e_{j0}}\right)\right]\\
&\times\exp\left[\sum_{i=1}^{m}(c_{i0}+\gamma_{it}\Delta c_i)\ln\left(\frac{I_{it}}{I_{i0}}\right)\right]\\
&\times\exp\left[\sum_{i=1}^{m}(c_{i0}+\omega_{it}\Delta c_i)\ln\left(\frac{y_{it}}{y_{i0}}\right)\right].\end{aligned}$$

Equating the discrete and continuous parameterizations results in the following weights:

$$\alpha_{ijt}=\left[\frac{(c_{ij0}/R_{ij0})\Delta R_{ij}-c_{ij0}\ln(R_{ijt}/R_{ij0})}{\Delta c_{ij}\ln(R_{ijt}/R_{ij0})-(c_{ijt}/R_{ijt}-c_{ij0}/R_{ij0})\Delta R_{ij}}\right],$$

$$\beta_{ijt}=\left[\frac{(c_{ij0}/e_{j0})\Delta e_j-c_{ij0}\ln(e_{jt}/e_{j0})}{\Delta c_{ij}\ln(e_{jt}/e_{j0})-(c_{ijt}/e_{jt}-c_{ij0}/e_{j0})\Delta e_j}\right],$$

$$\gamma_{it}=\left[\frac{(c_{i0}/I_{i0})\Delta I_i-c_{i0}\ln(I_{it}/I_{i0})}{\Delta c_i\ln(I_{it}/I_{i0})-(c_{it}/I_{it}-c_{i0}/I_{i0})\Delta I_i}\right],$$

$$\omega_{it}=\left[\frac{(c_{i0}/y_{i0})\Delta y_i-c_{i0}\ln(y_{it}/y_{i0})}{\Delta c_i\ln(y_{it}/y_{i0})-(c_{it}/y_{it}-c_{i0}/y_{i0})\Delta y_i}\right].$$

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